

A SUMMARY OF THE STRENGTH AND MODULUS OF ICE SAMPLES FROM MULTI-YEAR PRESSURE RIDGES

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ABSTRACT

Over two hundred unconfined compression tests were performed on vertical ice samples obtained from ten multi-year pressure ridges in the Beaufort Sea. The tests were performed on a closed-loop electrohydraulic testing machine at two strain rates (10^{-5} and 10^{-3} s $^{-1}$) and two temperatures (-20° and -5° C). This paper summarizes the sample preparation and testing techniques used in the investigation and presents data on the compressive strength and initial tangent modulus of the ice.

INTRODUCTION

Multi-year pressure ridges are thick accumulations of broken ice blocks that have survived at least one melt season. Surface melting and subsequent freezing of the water in the ridge cavities produce a massive ice feature with few or no voids. Multi-year pressure ridges in excess of 30 meters thick have been observed off the Beaufort Sea coast (1).

Little is known about the structure and strength of the ice in multi-year pressure ridges (2). This is surprising because multi-year pressure ridges may govern the design of offshore structures in exposed areas of the Beaufort and northern Chukchi seas. Data on the mechanical properties of the ice are needed so that offshore petroleum exploration can proceed in a safe, cost-effective manner.

This paper presents some of the results of a concentrated study designed to obtain a preliminary understanding of the structure and mechanical properties of ice samples from multi-year pressure ridges. The study included sampling in the southern Beaufort Sea, developing a variety of ice testing techniques, and performing 282 uniaxial compression, tension and conventional triaxial tests. Due to limited space, only the results of the uniaxial compression tests will be partly covered in this paper. Additional information on ice testing techniques and the test results can be found in Mellor et al. (3) and Cox et al. (4).

ICE DESCRIPTION

The field sampling program was conducted during the first two weeks of April 1981. Ten multi-year pressure ridges were sampled in the Beaufort Sea just north of Prudhoe Bay, Alaska. An effort was made to sample both large and small ridges to obtain a representative selection of vertical samples. A continuous core was also obtained from one ridge for detailed structural analyses.

Thin-section analyses of the 8.2-meter continuous core revealed that the ice structure was highly variable. Only about one-third of the core consisted of columnar ice, most of which was near the bottom. The upper portion of the core consisted largely of granular ice, mixed granular and columnar ice, and a one-meter-thick zone of pulverized, brecciated ice (4).

The ice samples from the pressure ridge sails (above sea level) had an average salinity of 0.7 ‰, while the samples from the keels had an average salinity of 1.5 ‰. The lower salinity of the ice in the upper portion of the ridge is caused by flushing of the brine by surface meltwater during the summer (5).

The ice in the sails also had a lower density. The average density of the test samples from the ridge sails was 0.876 Mg/m 3 ; the keel samples had an average density of 0.899 Mg/m 3 . The lower density of the sail samples can be attributed to high porosity and low salinity.

TEST METHODS

Uniaxial compression tests were performed on the ice samples from the ten multi-year pressure ridges to examine the magnitude and variation of ice strength within and between pressure ridges. The tests were conducted at two strain rates (10^{-5} and 10^{-3} s $^{-1}$) and two temperatures (20° and -5° C) so that the effects of these variables on the mechanical properties of the ice could also be evaluated. These strain rates and temperatures were chosen to bracket the conditions that would be expected in the ice off the Alaska coast under normal operating conditions.

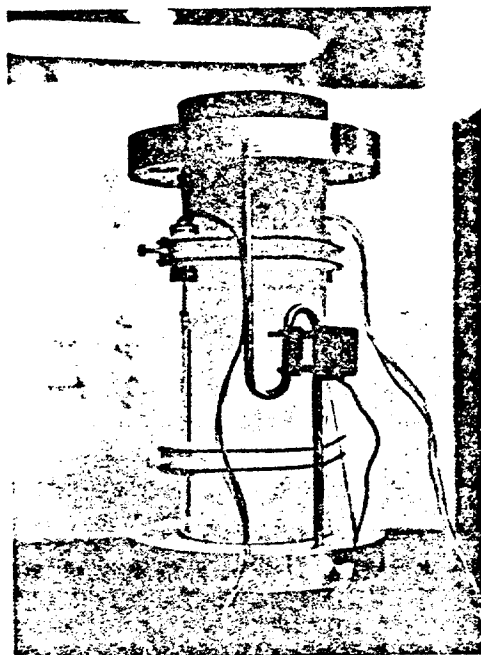


Figure 1. Instrumented test specimen.

All of the compression tests were performed on a closed-loop electrohydraulic testing machine. The machine had two actuators with capacities of 1.1 and 0.11 MN and a fast-response, high-flow-rate servo-valve. The load frame of the machine had a capacity of 2.2 MN. Strain rates were controlled by monitoring the full sample strain with an extensometer, which was attached to phenolic resin end caps bonded to the test specimens (Fig. 1). The tests were programmed to continue to 5% full sample strain to examine the post-yield behavior and residual strength of the ice. Since this resulted in considerable deformation of the test specimen, strain rates could not be controlled by the transducers mounted on the ice. Test temperatures were controlled to within 0.5°C by placing the sample in an environmental chamber mounted on the testing machine. The lower machine platen was also refrigerated to eliminate any thermal gradient problems.

Cylindrical test specimens were prepared from 10.7-cm-diameter cores. Samples were rough cut to length on a band saw, and the ends were milled square on a milling machine to produce a 25.4-cm-long test specimen. End caps were next bonded to the sample, and the sample was turned to a 10.2-cm diameter on a lathe. The finished sample also had slight fillets on the ends to minimize stress concentrations near the end planes. Every effort was made to produce properly sized, precision-machined test samples utilizing the standardized testing methods (6,7).

Load and full sample strains were monitored during each test, and axial strains on the center portion of the sample were measured with a pair of DCDTs. An instrumented sample is shown in Figure 1. Data were recorded on an XY plotter, a strip chart, and an FM magnetic tape recorder.

At the conclusion of the tests, strength and moduli values were determined from the force-displacement curves and compared to the ice brine volume, porosity and structure. In addition, statistical analyses were performed on the ice strength data to examine the variation of ice strength within and between pressure ridges.

TEST RESULTS

Summaries of the strength and initial tangent modulus data for each test condition are given in Tables 1 and 2. In general, standard deviations of the average property values are high; however, this is not surprising, because the test specimens exhibited a large variation in ice structure and porosity (4,8).

Both the strength and initial tangent modulus increase with increasing strain rate and decreasing temperature (Figs. 2 and 3). The strength and modulus also decrease with increasing porosity (Figs. 4 and 5). The effect of porosity on the strength and modulus were most pronounced in the 10^{-3} s^{-1} tests, where flaws and cavities play a more important role in brittle ice behavior.

The multi-year ridge ice strength and modulus showed no correlation with the ice brine volume, as observed for first-year sea ice (9). This is not surprising, because multi-year sea ice has a lower salinity and higher air content than first-year sea ice. Equations were therefore developed for calculating the total ice porosity (air plus brine volume) from the ice salinity, temperature and bulk density (10).

The test results indicate that the average strength of vertical, multi-year pressure ridge samples

Table 1. Summary of compressive strength data for multi-year pressure ridge ice samples.

UNIAXIAL COMPRESSIVE STRENGTH							
Maximum		Minimum		Mean		Number of samples	
(MPa)	(lbf/in. ²)	(MPa)	(lbf/in. ²)	(MPa)	(lbf/in. ²)		
<u>-5°C (23°F)</u>							
10 ⁻⁵ s ⁻¹	7.52	1090	0.47	68	2.34±1.08	340±157	71
10 ⁻³ s ⁻¹	10.90	1580	2.39	346	6.06±1.63	879±237	69
<u>-20°C (-4°F)</u>							
10 ⁻⁵ s ⁻¹	4.26	6.7	1.17	170	2.79±0.69	404±100	41
10 ⁻³ s ⁻¹	12.68	1838	7.03	1020	9.63±1.39	1396±202	41

Table 2. Summary of initial tangent modulus data for multi-year pressure ridge ice samples.

INITIAL TANGENT MODULUS							
Maximum		Minimum		Mean		Number of samples	
(GPa)	(lbf/in. ² x10 ⁶)	(GPa)	(lbf/in. ² x10 ⁶)	(GPa)	(lbf/in. ² x10 ⁶)		
<u>-5°C (23°F)</u>							
10 ⁻⁵ s ⁻¹	11.45	1.660	2.41	0.350	5.11±7.14	0.741±0.252	71
10 ⁻³ s ⁻¹	14.00	2.030	4.95	0.718	7.07±1.38	1.025±0.200	71
<u>-20°C (-4°F)</u>							
10 ⁻⁵ s ⁻¹	13.79	2.000	3.45	0.500	6.14±1.68	0.890±0.244	41
10 ⁻³ s ⁻¹	10.38	1.570	4.89	0.709	7.62±1.19	1.105±0.173	40

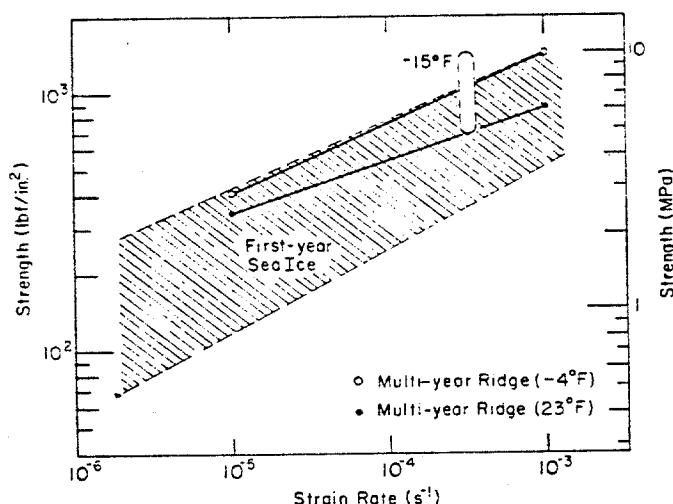


Figure 2. Average uniaxial compressive strength of vertical ridge ice samples vs strain rate of -5°C (23°F) and -20°C (-4°F). Strength data band of horizontal first-year sea ice samples (11) at -10°C (14°F) and data on multi-year sea ice (12) at -26°C (-15°F) are included for comparison.

is comparable to the average strength of horizontal first-year sea ice samples oriented in the hard fail direction given by Wang (11). The multi-year ridge ice strength values are also in general agreement with the multi-year sea ice strength data reported by Frederking and Timco (12).

For a given temperature and strain rate, the multi-year ridge ice modulus values are also similar to the modulus data for freshwater columnar and granular ice obtained by Traetteberg et al. (13). The 10⁻³ s⁻¹ results are comparable to dynamic, seismic determinations of Young's modulus for first-year sea ice (9).

In addition to an examination of the effect of ice temperature, strain rate and porosity on the mechanical properties of the ice, an analysis was performed to determine the effect of the ice structure on ice strength (4,8). A statistical analysis was also performed to examine the variation of ice strength within

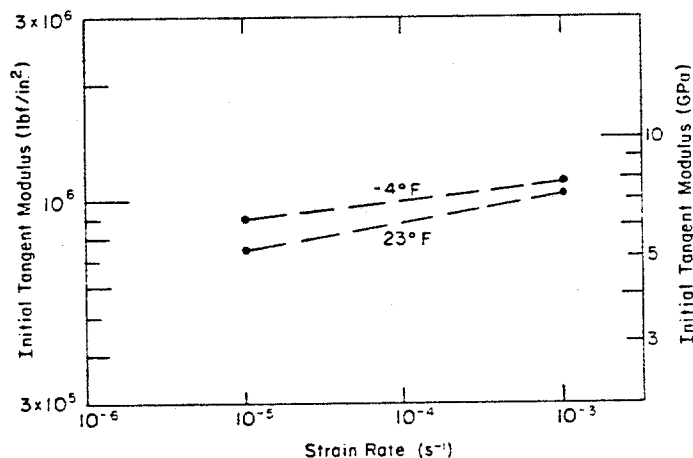
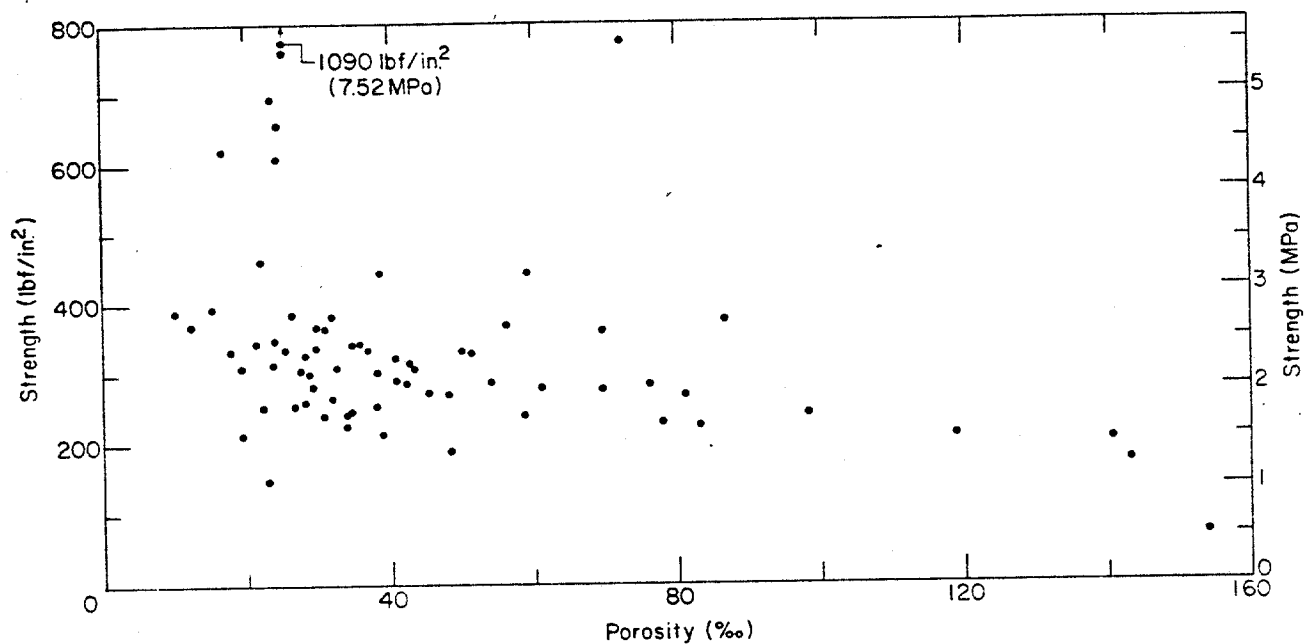


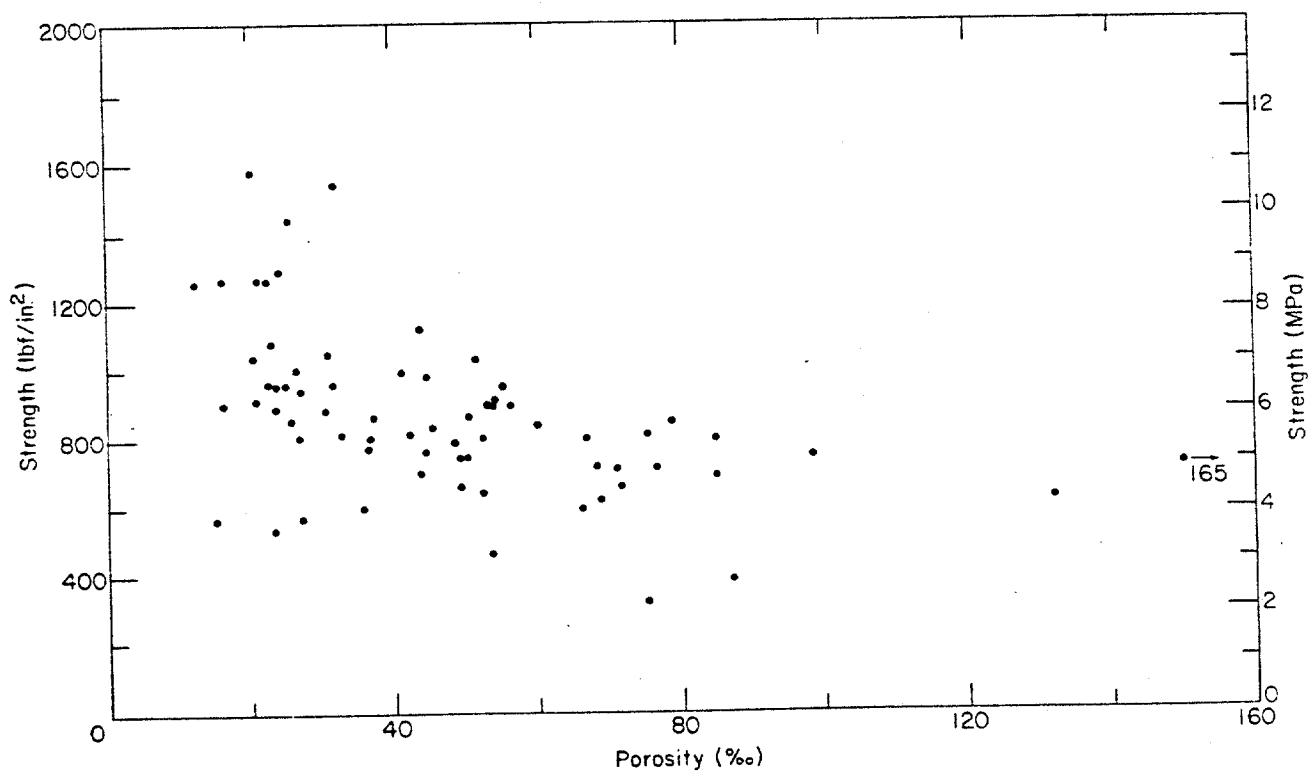
Figure 3. Average initial tangent modulus of ridge ice samples vs strain rate for tests at -5°C (23°F) and -20°C (-4°F).

and between multi-year pressure ridges (4,14).

Techniques and procedures were also developed to conduct constant-strain-rate uniaxial tension tests, constant-load uniaxial compression and tension tests, and convention triaxial tests. Most noteworthy is the triaxial testing equipment shown in Figure 6. The cell was designed so that the confining radial pressure on the sample could be ramped in constant proportion to the applied axial stress. For most engineering applications, it was felt that this loading arrangement was more realistic than applying a constant radial pressure at the beginning of a test and keeping the pressure constant. If friction and corrections for the sample geometry are neglected, the ratio of the confining pressure to the axial stress equals the ratio of the diameter of the piston entering the cell to the diameter of the piston in the upper cylinder. These newly developed tests will be used more extensively later in the project.

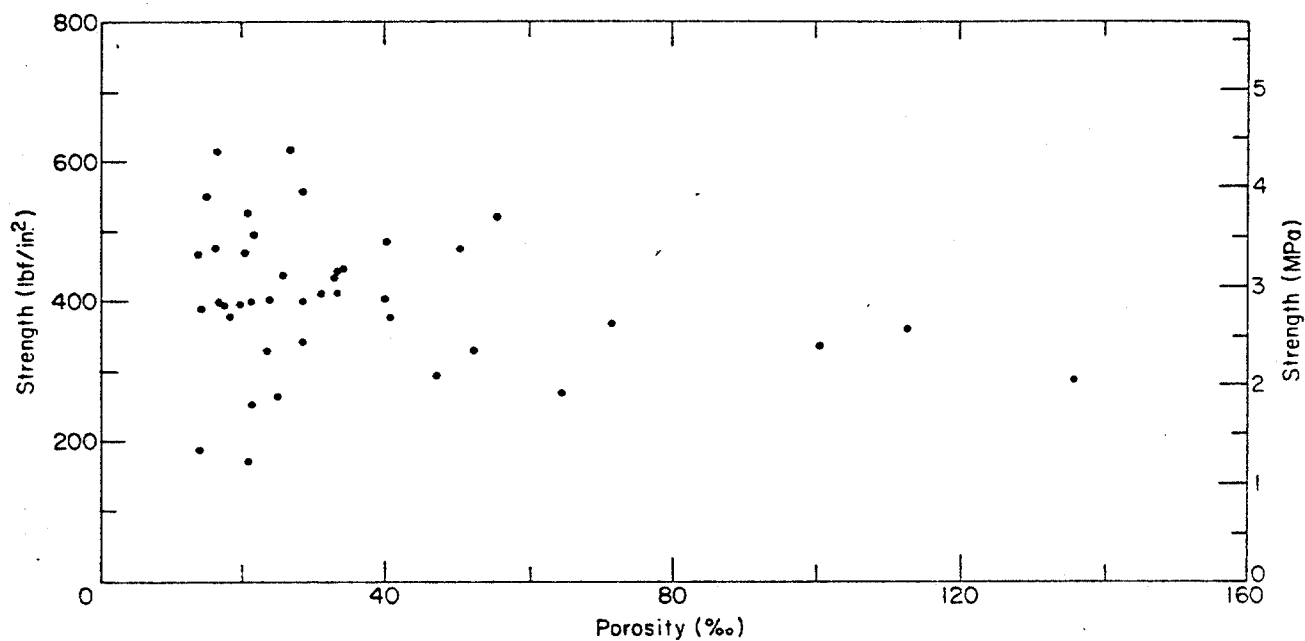


a. Tested at -5°C (23°F) and 10^{-5} s^{-1} .

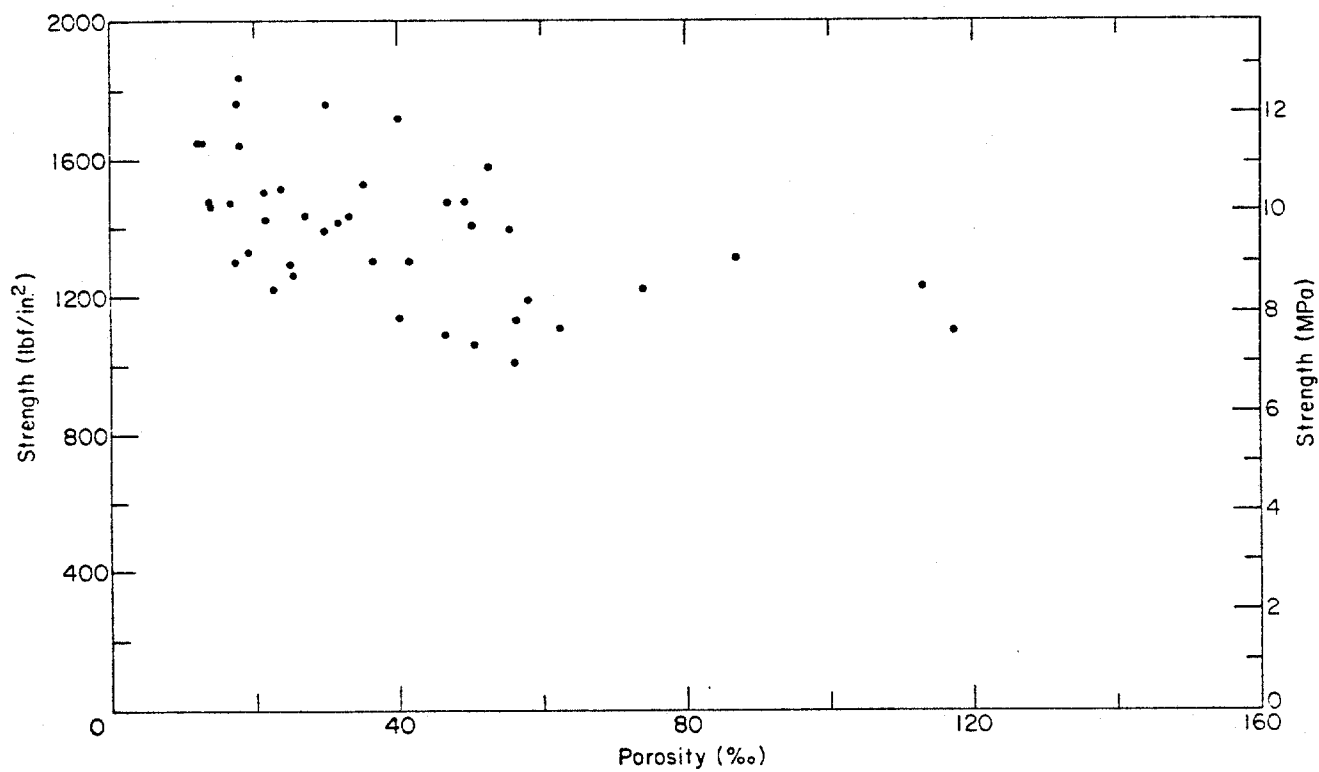


b. Tested at -5°C (23°F) and 10^{-3} s^{-1} .

Figure 4. Uniaxial compressive strength of ridge ice samples vs porosity.

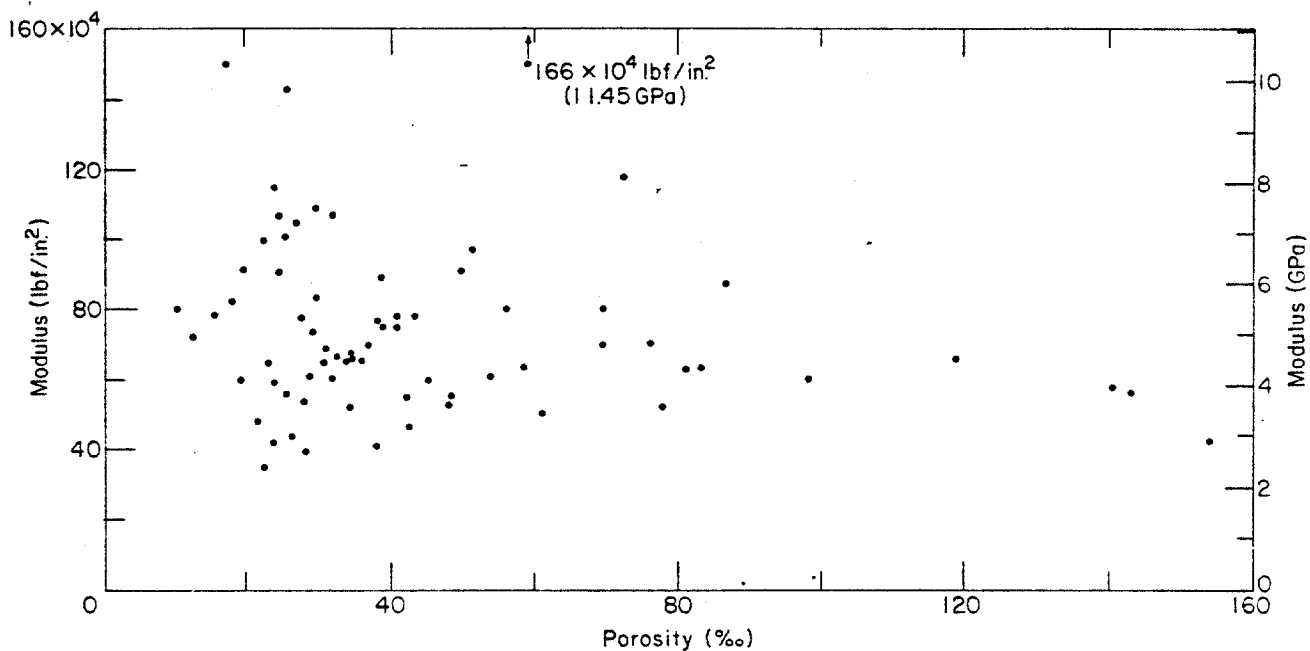


c. Tested at -20°C (-4°F) and 10^{-5} s^{-1} .

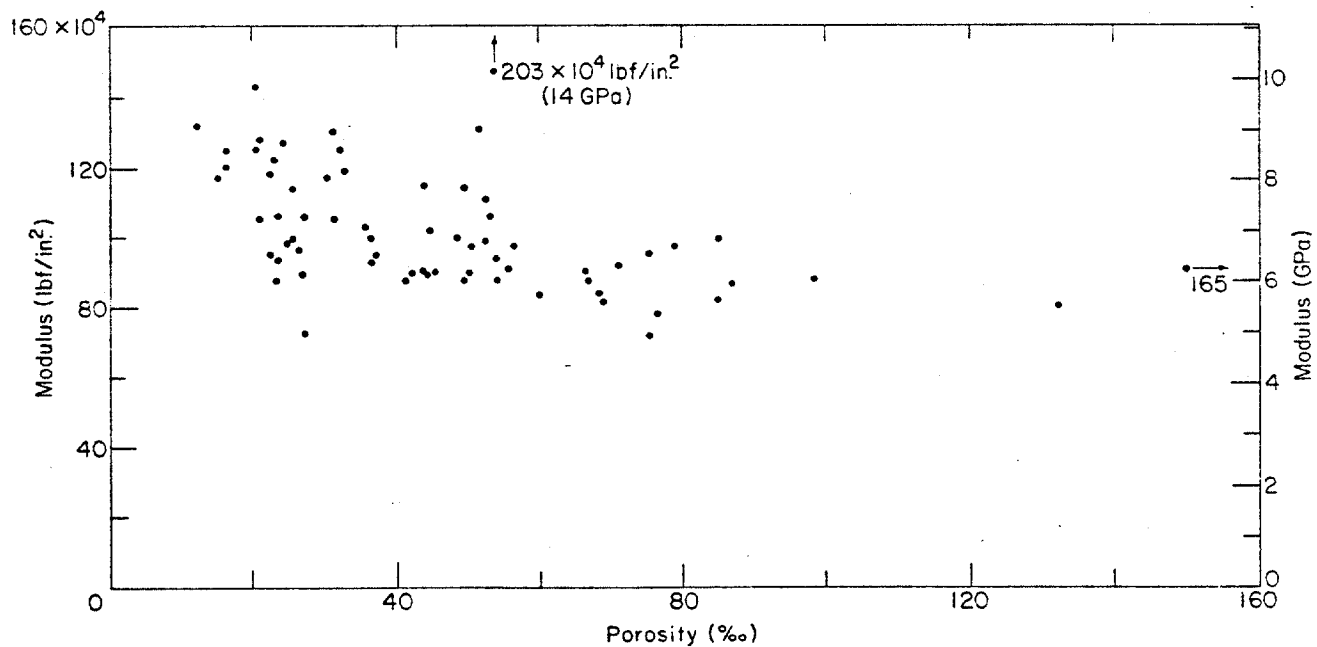


d. Tested at -20°C (-4°F) and 10^{-3} s^{-1} .

Figure 4 (cont'd). Uniaxial compressive strength of ridge ice samples vs porosity.

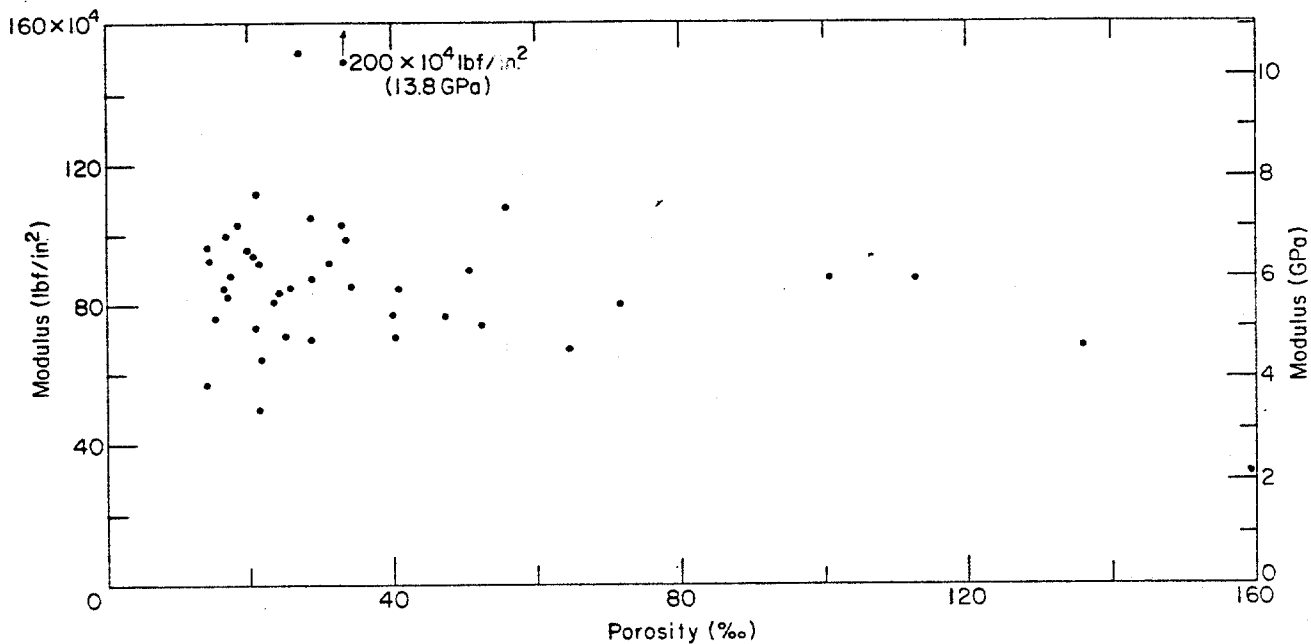


a. Tested at -5°C (23°F) and 10^{-5} s^{-1} .

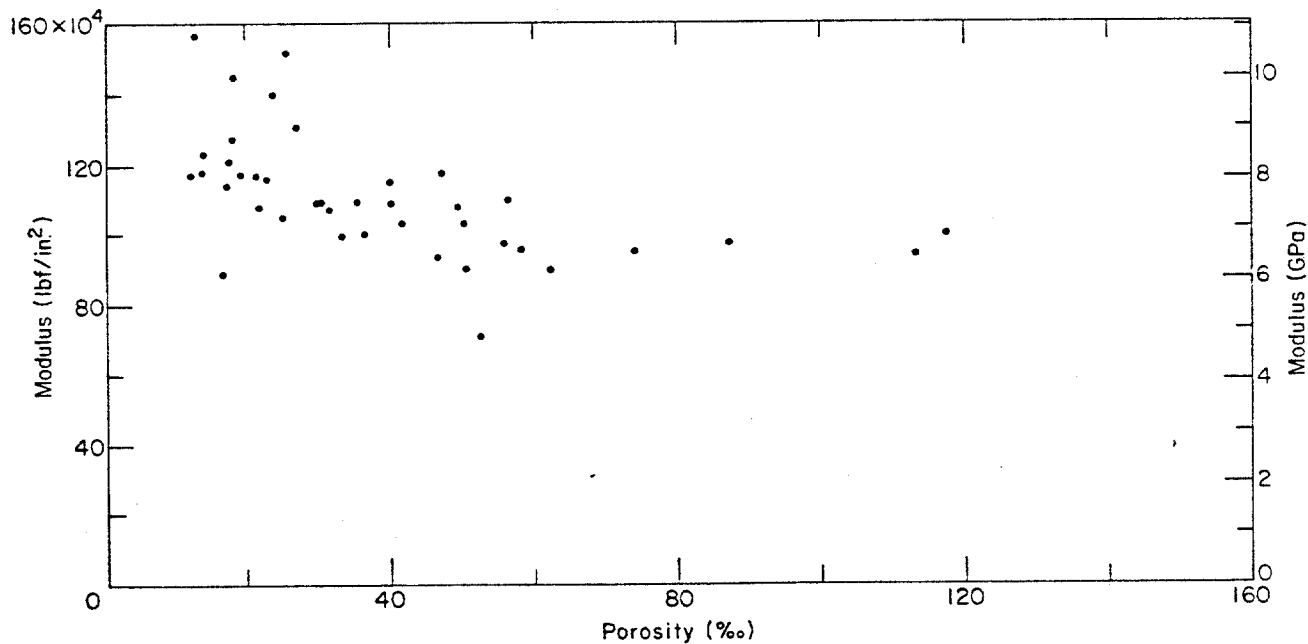


b. Tested at -5°C (23°F) and 10^{-3} s^{-1} .

Figure 5. Initial tangent modulus of ridge ice samples vs porosity.



c. Tested at -20°C (-4°F) and 10^{-5} s^{-1} .



d. Tested at -20°C (-4°F) and 10^{-3} s^{-1} .

Figure 5 (cont'd). Initial tangent modulus of ridge ice samples vs porosity.

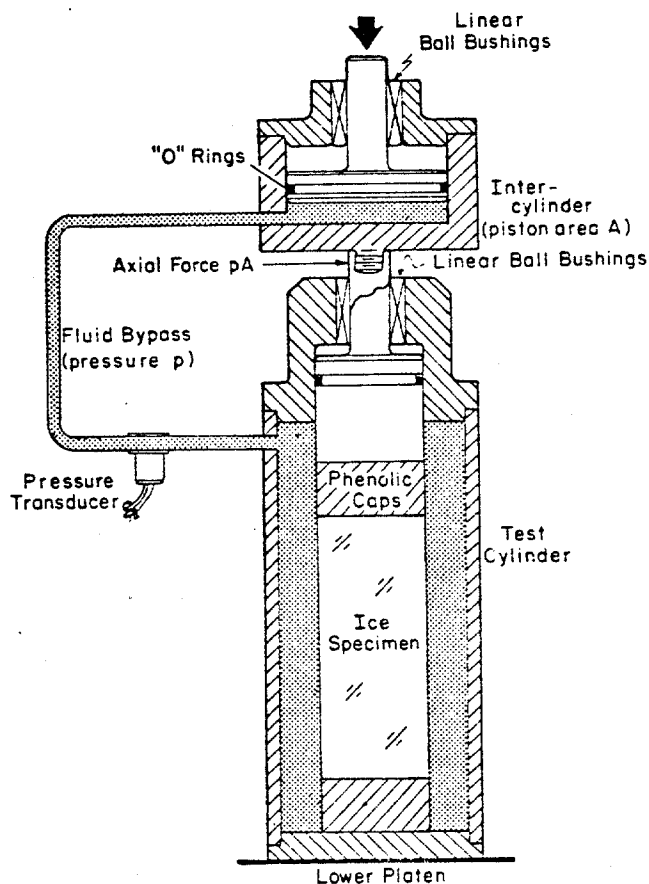


Figure 6. Schematic diagram of triaxial cell.

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